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Hydrogen Permeable Membrane

## BACKGROUND OF THE INVENTION

## Field of the Invention

The present invention relates to a hydrogen permeable membrane which has an excellent high-temperature amorphous stability, i.e., the quality of stably maintaining non-crystallinity for a long period of time when held in a high-temperature state, and which when used as a hydrogen permeable membrane in an apparatus such as a high-performance hydrogen purifier thus makes it possible to carry out a high-temperature heating operation that enhances the productivity of such a high-performance hydrogen purifier.

## Description of the Related Art

"Green energy" has attracted much attention in recent years as a way to counteract such phenomena as atmospheric pollution and global warming. In particular, energy systems which use hydrogen gas (one type of green energy) as the fuel, such as hydrogen fuel cells and hydrogen gas turbines, are currently under active investigation.

The high-purity hydrogen gas used as the fuel gas in these energy systems is produced from a hydrogen-containing feed gas such as a mixed gas obtained by electrolyzing water or a mixed gas obtained by steam reforming liquefied natural gas (LNG). Such production is typically carried out using a high-performance hydrogen purifier like that shown schematically in FIG. 1 which is divided into a left-hand chamber and a right-hand chamber by a hydrogen permeable membrane that is made of a material permeable only to hydrogen

and is reinforced at the periphery with a frame made of nickel or the like. A hydrogen-containing feed gas inlet and a bleed gas outlet are attached to the left-hand chamber, a high-purity hydrogen gas outlet is attached to the right-hand chamber, and a reaction chamber made of a material such as stainless steel is provided at the center. The feed gas is passed through the hydrogen permeable membrane with the reaction chamber heated to 200 to 300°C, thereby producing high-purity hydrogen gas by separative purification.

Hydrogen permeable membranes of this type which are made of non-crystalline nickel-zirconium or zirconium-nickel alloys are known. Processes for fabricating such membranes are known to include a liquid quenching process in which an alloy melt of a given composition is sprayed onto the surface of, for example, a rapidly rotating copper roll to effect solidification to a film thickness of 5 to 500  $\mu\text{m}$  (e.g., see JP-A 2000-256002).

To enhance productivity, there is a trend among such high-performance hydrogen purifiers toward operation under high-temperature heating. In prior-art high-performance hydrogen purifiers which use hydrogen permeable membranes made of non-crystalline nickel-zirconium alloys, during operation at a high heating temperature above 300°C, the hydrogen permeable membrane which exhibits a high hydrogen-separating and permeating ability owing to its non-crystallinity is readily subject to localized crystallization. In the areas that have crystallized, the hydrogen permeating and purifying ability of the membrane markedly declines, as a result of which the passage through the membrane and admixture of impurity gases other than hydrogen cannot be avoided.

Accordingly, such hydrogen permeable membranes have a relatively short service life.

There also exists a strong need for an even higher performance and a smaller size than has hitherto been achieved in high-performance hydrogen purifiers. This need has created in turn a strong desire for hydrogen permeable membranes endowed with a greater hydrogen-separating and permeating ability.

#### SUMMARY OF THE INVENTION

In light of the above, we have conducted investigations focused particularly on the above-described prior-art hydrogen permeable membranes made of non-crystalline nickel-zirconium and zirconium-nickel alloys which would enable operation of the above-described high-performance hydrogen purifiers under high-temperature heating.

The present invention provides a hydrogen permeable membrane made of a non-crystalline nickel-zirconium alloy composed of 44 to 75 atom % of nickel and 0.2 to 16 atom % of aluminum, with the balance being zirconium and unavoidable impurities; or made of a non-crystalline zirconium-nickel alloy composed of 44 to 75 atom % of zirconium and 0.2 to 16 atom % of aluminum, with the balance being nickel and unavoidable impurities. If the alloy used is a non-crystalline zirconium-nickel alloy, the nickel content is preferably not more than 43 atom %.

The aluminum included as an alloying element markedly improves the high-temperature amorphous stability of this hydrogen permeable membrane. Even in a high-temperature state above 300°C, crystallization is substantially suppressed,

enabling the non-crystalline structure to be maintained over a long period of time. The use of such a membrane in a high-performance hydrogen purifier, for example, enables this high-temperature heating operation to be carried out, as a result of which productivity can be further enhanced.

The invention also provides a hydrogen permeable membrane made of a non-crystalline nickel-zirconium alloy composed of 44 to 75 atom % of nickel and 0.2 to 12 atom % of vanadium and/or niobium, with the balance being zirconium and unavoidable impurities; or made of a non-crystalline zirconium-nickel alloy composed of 44 to 75 atom % of zirconium and 0.2 to 12 atom % of vanadium and/or niobium, with the balance being nickel and unavoidable impurities. If the alloy used is a non-crystalline zirconium-nickel alloy, the nickel content is preferably not more than 43 atom %.

The vanadium and/or niobium included as an alloying element markedly improves the hydrogen-separating and permeating ability of this hydrogen permeable membrane. Accordingly, employing this membrane in a high-performance hydrogen purifier contributes to higher performance and downsizing of the purifier.

The invention additionally provides a hydrogen permeable membrane made of a non-crystalline nickel-zirconium alloy composed of 44 to 75 atom % of nickel, 0.2 to 12 atom % of niobium, and 0.1 to 10 atom % of phosphorus, provided the combined amount of niobium and phosphorus is not more than 18 atom %, with the balance being zirconium and unavoidable impurities; or made of a non-crystalline zirconium-nickel alloy composed of 44 to 75 atom % of zirconium, 0.2 to 12 atom % of niobium, and 0.1 to 10 atom % of phosphorus, provided the combined amount of niobium and phosphorus is not more than 18

atom %, with the balance being nickel and unavoidable impurities. If the alloy used is a non-crystalline zirconium-nickel alloy, the nickel content is preferably not more than 43 atom %.

The niobium included as an alloying element greatly enhances the hydrogen-separating and permeating ability of this hydrogen permeable membrane, thus contributing to higher performance and downsizing of high-performance hydrogen purifiers, for example. The phosphorus included as an alloying element markedly enhances the high-temperature amorphous stability. Even in a high-temperature state above 300°C, crystallization is greatly suppressed, enabling the non-crystalline structure to be maintained over a long period of time. The use of such a membrane makes it possible to carry out a high-temperature heating operation in the above-described high-performance hydrogen purifier, for example, enabling productivity to be further enhanced.

Next, the composition of the non-crystalline nickel-zirconium alloy and the non-crystalline zirconium-nickel alloy in the inventive hydrogen-separation permeation membranes is described.

(A) Non-Crystalline Nickel-Zirconium Alloy:

(a-1) Nickel:

The nickel constituent within the non-crystalline nickel-zirconium alloy, when present together with the zirconium constituent, forms by means of quenching solidification a non-crystalline structure that exhibits a hydrogen-separating and permeating ability and also serves to enhance the strength of the membrane. At a nickel content of less than 44%, the high strength desired of the membrane cannot be ensured. On the

other hand, at a content of more than 75%, the relative proportion of zirconium within the alloy becomes small, which tends to result in a decline in the hydrogen-separating and permeating ability. Accordingly, the nickel content has been set at 44 to 75%. A nickel content of 50 to 69% is preferred.

(b-1) Aluminum:

As noted above, the aluminum constituent acts to enhance the high-temperature amorphous stability, and stably maintains the non-crystalline structure even at elevated temperatures above 300°C. However, at an aluminum content below 0.2%, a sufficient amorphous stability enhancing effect is not achieved. On the other hand, at a content greater than 16%, the hydrogen-separating and permeating ability of the membrane tends to decrease. Hence, the aluminum content has been set at 0.2 to 16%, and preferably 1 to 13%.

(c-1) Vanadium and Niobium:

These constituents form a non-crystalline structure together with the nickel and zirconium constituents. As noted above, vanadium and niobium serve to further enhance the hydrogen-separating and permeating ability. However, at a vanadium and niobium content of less than 0.2%, sufficient enhancement of this ability cannot be achieved. On the other hand, at a vanadium and niobium content of more than 12%, stable formation of a non-crystalline structure is difficult. Accordingly, the vanadium and niobium content has been set at 0.2 to 12%, and preferably 0.5 to 10%.

(d-1) Phosphorus:

As noted above, the phosphorus constituent improves the high-temperature amorphous stability and serves to stably ensure a non-crystalline structure even at elevated temperatures above 300°C. At a phosphorus content below 0.1%, sufficient enhancement of the amorphous stability is not achieved, whereas at a content above 10%, the hydrogen-separating and permeating ability of the membrane shows a tendency to decrease. Accordingly, the phosphorus content was set at 0.1 to 10%, and preferably 0.2 to 8%.

At a combined niobium and phosphorus content of more than 18%, the relative content of nickel and zirconium becomes too small, making it difficult to stably form a non-crystalline structure. For this reason, the combined amount of niobium and phosphorus has been set at not more than 18%.

(B) Non-Crystalline Zirconium-Nickel Alloy:

(a-2) Zirconium:

The zirconium constituent within the non-crystalline zirconium-nickel alloy, when present together with the nickel constituent, forms by means of quenching solidification a non-crystalline structure that exhibits a hydrogen-separating and permeating ability, and moreover enhances the hydrogen-separating and permeating ability of the membrane. At a zirconium content of less than 44%, the excellent hydrogen-separating and permeating ability desired of the membrane cannot be ensured. On the other hand, at a content of more than 75%, the relative proportion of nickel within the alloy becomes too small, which results in an abrupt drop in the membrane strength. Accordingly, the zirconium content has been set at 44 to 75%. A zirconium content of 50 to 70% is preferred.

If the nickel content in the non-crystalline zirconium-nickel alloy exceeds 43%, the membrane strength increases, but the relative proportion of zirconium becomes low, which tends to lower the hydrogen-separating and permeating ability of the membrane and thus makes it difficult to ensure a high hydrogen-separating and permeating ability. Hence, the upper limit in the nickel content was set at 43%.

(b-2) Aluminum:

As noted above, the aluminum constituent acts to enhance the high-temperature amorphous stability, and stably maintains the non-crystalline structure even at elevated temperatures above 300°C. However, at an aluminum content below 0.2%, a sufficient amorphous stability enhancing effect is not achieved. On the other hand, at a content greater than 16%, the hydrogen-separating and permeating ability of the membrane tends to decrease. Hence, the aluminum content has been set at 0.2 to 16%, and preferably 1 to 13%.

(c-2) Vanadium and Niobium:

These constituents form a non-crystalline structure together with the nickel and zirconium constituents. As noted above, vanadium and niobium serve to further enhance the hydrogen-separating and permeating ability. However, at a vanadium and niobium content of less than 0.2%, sufficient enhancement of this ability cannot be achieved. On the other hand, at a vanadium and niobium content of more than 20%, stable formation of a non-crystalline structure is difficult. Accordingly, the vanadium and niobium content has been set at 0.2 to 20%, and preferably 0.5 to 15%.



(d-2) Phosphorus:

As noted above, the phosphorus constituent improves the high-temperature amorphous stability and serves to stably ensure a non-crystalline structure even at elevated temperatures above 300°C. At a phosphorus content below 0.1%, sufficient enhancement of the amorphous stability is not achieved, whereas at a content above 15%, the hydrogen-separating and permeating ability of the membrane tends to decrease. Accordingly, the phosphorus content was set at 0.1 to 15%, and preferably 0.2 to 10%.

At a combined niobium and phosphorus content of more than 18%, the relative content of nickel and zirconium becomes too small, making it difficult to stably form a non-crystalline structure. For this reason, the combined amount of niobium and phosphorus has been set at not more than 18%.

#### BREIF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view of a high-performance hydrogen purifier.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The hydrogen permeable membrane of the invention is illustrated more fully in the following examples.

Inventive Hydrogen permeable membranes 1 to 29, and Prior-Art Hydrogen permeable membranes 1 to 12

Sponge zirconium of 99.5% purity, nickel of 99.9% purity and aluminum of 99.9% purity were used as the starting materials. These starting materials were blended in specific proportions and argon arc melted in a high-purity argon

atmosphere to form 300 g ingots. The ingots were re-melted in a melting furnace within an argon atmosphere, and the melt was sprayed at a pressure of 0.05 MPa onto the surface of a water-cooled copper roll rotating at a speed of 33 m/s (nickel-zirconium alloys) or 20 m/s (zirconium-nickel alloys), thereby forming nickel-zirconium (or zirconium-nickel) alloy foils of the compositions shown in Table 1 (nickel-zirconium alloys) or Table 2 (zirconium-nickel alloys) which had a width of 30 mm and a thickness of 30  $\mu$ m (nickel-zirconium alloys) or a width of 30 mm and a thickness of 50  $\mu$ m (zirconium-nickel alloys). Each of these foils was cut to planar dimensions of 30x100 mm, thereby preparing inventive hydrogen permeable membranes 1 to 13 (nickel-zirconium alloys; Table 1) and 14 to 29 (zirconium-nickel alloys; Table 2), and preparing also prior-art hydrogen permeable membranes 1 to 6 (nickel-zirconium alloys; Table 1) and 7 to 12 (zirconium-nickel alloys; Table 2) which did not contain aluminum as an alloying element.

The microstructures of these hydrogen permeable membranes were examined by x-ray diffraction analysis and found in each case to be non-crystalline.

A palladium thin film was then formed by vapor deposition to a thickness of 10 nm on both sides of each of the above hydrogen permeable membranes. The membrane was then placed between two nickel reinforcing frames, each having a lateral outside dimension of 35 mm, a vertical outside dimension of 105 mm, a frame width of 5 mm and a frame thickness of 0.2 mm, and the membrane was ultrasonically welded to the reinforcing frames and thereby fixed. The membrane was then installed in this reinforced state within the reaction chamber of a high-performance hydrogen purifier of the construction shown in

FIG. 1, and the interior of the reaction chamber was heated to 300°C or 350°C.

In the case of inventive hydrogen permeable membranes 1 to 13 and prior-art hydrogen permeable membranes 1 to 6, a hydrogen-containing feed gas obtained by steam reforming LNG and containing 66.5 vol % of  $H_2$ , 17 vol % of  $CO_2$  and 0.5 vol % of CO was fed through an inlet into the left-hand reaction chamber while holding the internal pressure within this chamber at 0.3 MPa.

In the case of inventive hydrogen permeable membranes 14 to 29 and prior-art hydrogen permeable membranes 7 to 12, a hydrogen-containing feed gas obtained by steam reforming methanol and containing 70 vol % of  $H_2$ , 22 vol % of  $CO_2$  and 0.5 vol % of CO was fed through an inlet into the left-hand reaction chamber while holding the internal pressure within this chamber at 0.3 MPa.

At the same time, hydrogen purifying treatment in which the separated and purified high-purity hydrogen gas was drawn off from the outlet while holding the internal pressure in the right-hand chamber to 0.1 MPa was carried out, and the flow rate of the separated and purified high-purity hydrogen gas was measured with a gas flow meter 30 minutes after the start of treatment at reaction chamber heating temperatures of 300°C and 350°C. The separated and purified high-purity hydrogen gas was also analyzed with a gas chromatograph every 100 hours following the start of hydrogen purification treatment, and the treatment time until the  $CO_2$  gas content within the separated and purified high-purity hydrogen gas rose to 100 ppm was measured. This treatment time was regarded as the life of the membrane. The results of these measurements are shown in Tables 1 and 2.

Table 1

Type of membrane		Composition (atom %)			Reaction temperature of 300°C		Reaction temperature of 350°C	
		Ni	Al	Zr + impurities	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)
Hydrogen permeable membranes according to invention	1	44.12	9.52	balance	34.8	2,200	46.2	900
	2	50.10	9.77	balance	33.5	2,400	45.0	1,000
	3	54.17	9.45	balance	32.1	2,600	43.0	1,200
	4	60.75	9.44	balance	30.8	2,500	41.4	1,100
	5	65.51	9.50	balance	30.0	2,500	40.5	1,100
	6	69.57	9.34	balance	28.9	2,400	39.3	1,000
	7	74.92	9.63	balance	27.6	2,300	38.2	900
	8	60.80	0.52	balance	34.3	2,300	45.1	900
	9	61.24	1.16	balance	33.6	2,500	44.6	1,100
	10	61.10	3.75	balance	32.1	2,600	43.0	1,200
	11	61.56	7.90	balance	30.5	2,500	41.2	1,100
	12	61.11	12.96	balance	28.9	2,400	39.2	1,000
	13	60.71	15.91	balance	27.5	2,200	38.0	800
Prior-art Hydrogen permeable membranes	1	50.16	--	balance	35.2	1,900	46.3	600
	2	60.81	--	balance	33.2	2,100	44.3	700
	3	69.73	--	balance	29.1	2,000	39.1	600
	4	62.34	Cu: 0.82	balance	33.4	2,100	44.6	700
	5	60.50	Cu: 5.63	balance	30.9	2,100	41.6	600
	6	58.70	Cu: 14.35	balance	27.8	1,900	38.1	600

Table 2

Type of membrane		Composition (atom %)			Reaction temperature of 300°C		Reaction temperature of 350°C	
		Zr	Al	Ni + impurities	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)
Hydrogen permeable membranes according to invention	14	44.08	14.78	balance (41.14)	24.3	2,200	33.4	900
	15	47.25	9.89	balance (42.86)	25.4	2,300	34.5	900
	16	50.63	6.61	balance (42.76)	26.1	2,400	34.9	1,000
	17	54.57	6.75	balance (38.68)	26.8	2,500	35.8	1,100
	18	58.29	6.21	balance (35.50)	27.3	2,600	36.5	1,200
	19	62.43	6.24	balance (31.33)	28.4	2,500	37.8	1,100

	20	66.40	6.47	balance (27.13)	29.2	2,400	38.4	1,000
	21	71.69	6.56	balance (21.75)	29.9	2,200	39.5	900
	22	74.85	6.26	balance (18.89)	30.7	2,100	40.3	800
	23	64.48	0.53	balance (34.99)	30.8	2,200	40.5	900
	24	64.35	1.19	balance (34.46)	30.2	2,300	39.7	1,000
	25	64.16	3.65	balance (32.19)	29.0	2,400	38.3	1,100
	26	64.05	7.89	balance (28.06)	28.3	2,500	37.8	1,100
	27	63.95	10.10	balance (25.95)	27.0	2,500	36.4	1,100
	28	59.35	14.93	balance (25.72)	25.9	2,400	34.8	1,000
	29	56.61	17.93	balance (25.45)	24.4	2,200	33.6	900
Prior-art hydrogen permeable membranes	7	59.53	--	balance (40.47)	27.3	1,800	36.5	500
	8	65.83	--	balance (34.17)	29.1	2,000	38.6	600
	9	71.51	--	balance (28.49)	30.6	1,900	40.4	600
	10	61.39	Cu: 0.56	balance (38.05)	28.4	2,000	37.9	600
	11	60.45	Cu: 4.83	balance (34.72)	25.4	1,900	34.5	500
	12	55.31	Cu: 14.89	balance (29.80)	24.2	1,800	33.3	500

Inventive Hydrogen permeable membranes 30 to 79, and Prior-Art Hydrogen permeable membranes 13 to 24

Sponge zirconium of 99.5% purity, nickel shot of 99.9% purity, Ni-51% V master alloy, and Ni-60% Nb master alloy were used as the starting materials. These starting materials were blended in specific proportions and argon arc melted in a high-purity argon atmosphere to form 300 g ingots. The ingots were re-melted in a melting furnace within an argon atmosphere, and the melt was sprayed at a pressure of 0.03 MPa onto the surface of a water-cooled copper roll rotating at a speed of 25 m/s (nickel-zirconium alloys) or 18 m/s (zirconium-nickel alloys), thereby forming nickel-zirconium alloy foils of the compositions shown in Table 3 which had a

width of 20 mm and a thickness of 30  $\mu\text{m}$  and zirconium-nickel alloy foils of the composition shown in Table 4 which had a width of 20 mm and a thickness of 40  $\mu\text{m}$ . Each of these foils was cut to dimensions of 20x80 mm, thereby preparing hydrogen permeable membranes 30 to 79 according to the invention and preparing also comparative hydrogen permeable membranes 13 to 24 which did not contain vanadium and niobium as alloying elements and corresponded to the foregoing prior-art hydrogen permeable membranes.

The microstructures of these hydrogen permeable membranes were examined by x-ray diffraction analysis and found in each case to be non-crystalline.

A palladium thin film was then formed by vapor deposition to a thickness of 10 nm on both sides of each of the above hydrogen permeable membranes. The membrane was then placed between two nickel reinforcing frames, each having a lateral outside dimension of 25 mm, a vertical outside dimension of 85 mm, a frame width of 5 mm and a frame thickness of 0.2 mm, and the membrane was ultrasonically welded to the reinforcing frames and thereby fixed. The membrane was then installed in this reinforced state within the reaction chamber of a high-performance hydrogen purifier of the construction shown in FIG. 1.

In the case of nickel-zirconium alloys, the interior of the reaction chamber was heated to 300°C, a hydrogen-containing feed gas obtained by steam reforming methanol and containing 70 vol % of  $\text{H}_2$  and 22 vol % of  $\text{CO}_2$ , with the balance being high-temperature steam and other components, was fed through an inlet into the left-hand reaction chamber while holding the internal pressure within this chamber at 0.5 MPa.

In the case of zirconium-nickel alloys, the interior of the reaction chamber was heated to 300°C, a hydrogen-containing feed gas obtained by steam reforming town gas and containing 66.5 vol % of H<sub>2</sub> and 20 vol % of CO<sub>2</sub>, with the balance being high-temperature steam and other components, was fed through an inlet into the left-hand reaction chamber while holding the internal pressure within this chamber at 0.5 MPa.

At the same time, hydrogen purifying treatment in which the separated and purified high-purity hydrogen gas is drawn off from the outlet while holding the internal pressure within the right-hand chamber to 0.1 MPa was carried out, and the flow rate of the separated and purified high-purity hydrogen gas was measured with a gas flow meter 30 minutes after the start of treatment. The measurement results are shown in Tables 3 and 4. The hydrogen separating and permeating abilities of the membranes were rated based on these results.

The content of CO<sub>2</sub> gas, which is an impurity, in the above-described separated and purified high-purity hydrogen gases was measured using a gas chromatograph. In each case, CO<sub>2</sub> was not detected.

Table 3

Type of membrane		Composition (atom %)				High-purity hydrogen gas flow rate (ml/min)
		Ni	V	Nb	Zr + impurities	
Hydrogen	30	44.11	5.24	--	balance (50.65)	48.3
	31	50.64	5.33	--	balance (44.03)	47.5
	32	61.42	5.29	--	balance (33.29)	44.2
	33	68.83	5.30	--	balance (25.87)	42.6
	34	74.68	5.21	--	balance (20.11)	39.3

permeable membranes according to invention	35	44.25	--	1.55	balance (54.20)	48.1
	36	50.31	--	1.47	balance (48.22)	47.3
	37	61.33	--	1.49	balance (37.18)	44.2
	38	68.71	--	1.53	balance (29.76)	42.3
	39	74.93	--	1.54	balance (23.53)	39.0
	40	63.50	0.22	--	balance (36.28)	39.7
	41	63.06	0.58	--	balance (36.36)	42.8
	42	62.42	3.50	--	balance (34.08)	45.2
	43	62.14	9.87	--	balance (27.99)	48.1
	44	61.98	11.96	--	balance (26.06)	47.5
	45	63.39	--	0.26	balance (36.35)	40.0
	46	63.21	--	0.54	balance (36.25)	43.4
	47	62.86	--	5.62	balance (31.52)	45.5
	48	62.08	--	9.91	balance (28.01)	47.7
	49	61.84	--	11.88	balance (26.28)	47.3
	50	65.42	0.08	0.15	balance (34.35)	39.4
	51	64.15	0.26	0.31	balance (35.28)	43.1
	52	59.17	2.31	3.28	balance (35.24)	45.7
	53	54.61	3.15	6.79	balance (35.45)	48.4
	54	50.24	7.25	4.70	balance (37.81)	49.2
Comparative hydrogen permeable membranes	13	50.21	--	--	balance (49.79)	35.2
	14	61.07	--	--	balance (38.93)	33.2
	15	68.62	--	--	balance (31.38)	30.0
	16	63.54	--	Cu: 0.55	balance (35.91)	33.5
	17	61.42	--	Cu: 5.25	balance (33.33)	30.7
	18	53.52	--	Cu: 11.85	balance (34.63)	29.0



Table 4

Type of membrane		Composition (atom %)				High-purity hydrogen gas flow rate (ml/min)
		Zr	V	Nb	Ni + impurities	
Hydrogen permeable membranes according to invention	55	44.11	12.96	--	balance (42.89)	37.5
	56	50.06	9.83	--	balance (40.11)	39.7
	57	60.74	9.66	--	balance (29.60)	41.1
	58	69.65	9.73	--	balance (20.62)	43.3
	59	74.88	9.68	--	balance (15.44)	43.7
	60	44.07	--	13.31	balance (42.62)	37.1
	61	50.45	--	6.65	balance (42.90)	39.3
	62	61.07	--	6.55	balance (32.38)	40.4
	63	69.77	--	6.60	balance (23.63)	41.9
	64	74.51	--	6.62	balance (18.87)	42.2
	65	58.56	0.26	--	balance (41.18)	37.4
	66	58.60	0.58	--	balance (40.82)	38.7
	67	58.61	3.50	--	balance (37.89)	40.1
	68	58.64	14.86	--	balance (26.50)	43.4
	69	58.61	19.90	--	balance (21.49)	43.9
	70	60.27	--	0.23	balance (39.50)	37.6
	71	60.25	--	0.54	balance (39.21)	38.9
	72	60.24	--	2.91	balance (36.85)	40.2
	73	60.31	--	14.93	balance (24.76)	42.9
	74	60.28	--	19.87	balance (19.85)	43.3
	75	65.73	0.19	0.07	balance (34.01)	37.2
	76	63.35	0.40	0.19	balance (36.06)	39.1
	77	59.47	4.32	5.29	balance (30.92)	41.4
	78	56.59	6.19	8.73	balance (28.49)	42.2

	79	51.37	9.51	10.46	balance (28.66)	42.8
Prior-art hydrogen permeable membranes	19	60.05	--	--	balance (39.95)	29.2
	20	66.24	--	--	balance (33.76)	31.0
	21	72.37	--	--	balance (27.63)	32.4
	22	60.45	--	Cu: 0.63	balance (38.92)	29.9
	23	61.31	--	Cu: 5.54	balance (33.15)	27.0
	24	53.52	--	Cu: 19.52	balance (26.96)	25.2

Inventive Hydrogen permeable membranes 80 to 107, and Prior-Art Hydrogen permeable membranes 25 to 36

Sponge zirconium of 99.5% purity, nickel shot of 99.9% purity, Ni-60% Nb master alloy, and Ni-25% P master alloy were used as the starting materials. These starting materials were blended in specific proportions and argon arc melted in a high-purity argon atmosphere to form 300 g ingots. The ingots were re-melted in a melting furnace within an argon atmosphere, and the melt was sprayed at a pressure of 0.03 MPa onto the surface of a water-cooled copper roll rotating at a speed of 25 m/s (nickel-zirconium alloys) or 18 m/s (zirconium-nickel alloys), thereby forming nickel-zirconium alloy foils of the compositions shown in Table 5 which had a width of 20 mm and a thickness of 30  $\mu\text{m}$  and zirconium-nickel alloy foils of the composition shown in Table 6 which had a width of 20 mm and a thickness of 40  $\mu\text{m}$ . Each of these foils was cut to dimensions of 20×80 mm, thereby preparing hydrogen permeable membranes 80 to 107 according to the invention and preparing also prior-art hydrogen permeable membranes 25 to 36 which did not contain niobium and phosphorus as alloying elements and corresponded to the foregoing prior-art hydrogen permeable membranes.

The microstructures of these hydrogen permeable membranes were examined by x-ray diffraction analysis and found in each case to be non-crystalline.

A palladium thin film was then formed by vapor deposition to a thickness of 10 nm on both sides of each of the above hydrogen permeable membranes. The membrane was then placed between two nickel reinforcing frames, each having a lateral outside dimension of 25 mm, a vertical outside dimension of 85 mm, a frame width of 5 mm and a frame thickness of 0.2 mm, and the membrane was ultrasonically welded to the reinforcing frames and thereby fixed. The membrane was then installed in this reinforced state within the reaction chamber of a high-performance hydrogen purifier of the construction shown in FIG. 1, and the interior of the reaction chamber was heated to 300°C or 350°C in each case. A hydrogen-containing feed gas obtained by steam reforming methanol and containing 70 vol % of H<sub>2</sub> and 22 vol % of CO<sub>2</sub>, with the balance being high-temperature steam and other components, was fed through an inlet into the left-hand reaction chamber while holding the internal pressure within this chamber at 0.4 MPa. At the same time, hydrogen purifying treatment in which the separated and purified high-purity hydrogen gas is drawn off from the outlet while holding the internal pressure within the right-hand chamber to 0.1 MPa was carried out, and the flow rate of the separated and purified high-purity hydrogen gas was measured with a gas flow meter 1 hour after the start of treatment. The hydrogen separating and permeating abilities of the membranes were rated based on these results. In addition, the content of CO<sub>2</sub> gas, which is an impurity, within the separated and purified high-purity hydrogen gas was analyzed with a gas chromatograph every 100 hours following the start of hydrogen

purification treatment, and the treatment time until the CO<sub>2</sub> gas content within the separated and purified high-purity hydrogen gas rose to 100 ppm was measured. This treatment time was regarded as the life of the membrane. The results of these measurements are shown in Tables 5 and 6.

Table 5

Type of membrane		Composition (atom %)				Reaction temperature of 300°C		Reaction temperature of 350°C	
		Ni	Nb	P	Zr + impurities	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)
Hydrogen permeable membranes according to invention	80	44.08		1.53	balance	35.8	2,900	48.1	1,300
	81	51.13	2.28	1.64	balance	34.4	3,100	46.3	1,400
	82	59.26	2.21	1.52	balance	32.9	3,200	44.3	1,500
	83	68.94	2.19	1.57	balance	30.7	3,100	41.8	1,400
	84	74.78	2.23	1.50	balance	29.3	2,900	39.0	1,300
	85	62.53	2.27	3.70	balance	30.6	3,100	42.1	1,400
	86	62.34	0.23	3.72	balance	32.0	3,100	43.4	1,400
	87	57.85	0.69	3.67	balance	34.7	3,000	46.4	1,400
	88	57.37	9.86	3.75	balance	36.1	2,900	48.0	1,300
	89	60.51	11.85	0.13	balance	34.1	2,900	46.4	1,200
	90	60.34	5.15	0.24	balance	33.1	3,100	45.0	1,400
	91	56.44	5.18	7.91	balance	30.5	3,100	41.6	1,400
	92	54.72	5.14	9.78	balance	29.6	3,000	40.4	1,100
Prior-art hydrogen permeable membranes	25	50.20	--	--	balance	27.3	1,900	35.3	600
	26	60.85	--	--	balance	25.6	2,100	34.2	700
	27	69.54	--	--	balance	22.8	2,000	30.7	600
	28	62.40	--	Cu: 0.55	balance	26.1	2,100	33.8	700
	29	60.50	--	Cu: 5.25	balance	23.8	2,100	31.7	600
	30	58.70	--	Cu: 9.63	balance	21.6	1,900	29.6	600

Table 6

Type of membrane		Composition (atom %)				Reaction temperature of 300°C		Reaction temperature of 350°C	
		Zr	Nb	P	Ni + impurities	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)	High-purity hydrogen gas flow rate (ml/min)	Life of membrane (hours)
Hydrogen permeable membranes according to invention	93	44.13		6.37	balance (42.91)	30.1	2,900	40.1	1,300
			6.59						
	94	50.37		2.14	balance (42.45)	30.9	2,900	40.3	1,300
			5.04						
	95	60.22		2.12	balance (33.97)	32.6	3,000	42.4	1,400
			3.69						
	96	65.91		2.17	balance (28.28)	34.3	3,100	44.4	1,400
			3.64						
	97	74.65		2.20	balance (19.48)	35.0	2,900	45.5	1,300
			3.67						
	98	62.53		1.55	balance (35.71)	31.2	3,000	40.5	1,400
			0.21						
	99	62.34		1.57	balance (35.01)	31.9	3,000	41.4	1,400
			1.08						
	100	58.72		1.54	balance (29.88)	33.8	2,900	43.7	1,300
			9.86						
Prior-art hydrogen permeable membranes	101	55.26	14.31	1.52	balance (28.91)	34.6	2,800	44.6	1,300
	102	50.37	19.83	1.59	balance (28.21)	35.1	2,700	45.2	1,200
	103	61.29		0.13	balance (31.27)	34.9	2,900	44.9	1,200
			7.31						
	104	60.50		0.26	balance (31.96)	34.5	3,000	44.5	1,400
			7.28						
	105	56.01		4.79	balance (31.92)	33.7	3,100	43.8	1,400
			7.28						
	106	52.37		9.55	balance (30.74)	32.1	3,100	42.0	1,400
			7.34						
	107	47.25		14.89	balance (30.56)	30.4	3,000	40.0	1,300
			7.30						
	31	58.67	--	--	balance (41.33)	24.1	1,800	32.3	500
	32	65.12	--	--	balance (34.88)	26.3	2,000	34.6	600
	33	70.38	--	--	balance (29.62)	27.0	1,900	35.8	600
	34	60.84	--	Cu: 0.58	balance (38.58)	25.1	2,000	33.6	600
	35	59.28	--	Cu: 5.17	balance (35.55)	22.5	1,900	31.0	500
	36	58.63	--	Cu: 14.21	balance (27.16)	21.6	1,800	29.6	500

### Industrial Applicability

As is apparent from the above tables, a comparison of inventive hydrogen permeable membranes 1 to 29 with prior-art hydrogen permeable membranes 1 to 12 which do not contain aluminum as an alloying element shows that even when aluminum

is present as an alloying element, there is substantially no change in the production and flow rate of separated and purified high-purity hydrogen gas (i.e., in the hydrogen separating and permeating action) at a normal heating and operating temperature of 300°C and even at a high-temperature heating and operating temperature of 350°C. However, because inventive hydrogen permeable membranes 1 to 29 which contain aluminum as an alloying element all have excellent high-temperature amorphous stability, they clearly exhibit a much longer service life than prior-art hydrogen-separation permeation membranes 1 to 12, particularly in high-temperature heating operation.

As mentioned above, the hydrogen permeable membranes of the invention have excellent high-temperature amorphous stability, with crystallization being clearly suppressed even at elevated temperatures above 300°C so that a non-crystalline microstructure is maintained. Accordingly, this enables the high-temperature heating operation of equipment such as high-performance hydrogen purifiers, contributing to a further improvement in productivity.

As is also apparent from the above tables, a comparison of inventive hydrogen permeable membranes 30 to 79 which contain vanadium and/or niobium as alloying elements with comparative hydrogen permeable membranes 13 to 24 which do not contain these elements clearly shows that, due to the effects of the vanadium and/or niobium present as alloying elements, the former membranes exhibit a much better hydrogen-separating and permeating ability than the latter membranes.

As noted above, because these hydrogen permeable membranes according to the invention exhibit a much better hydrogen-separating and permeating ability, they can

contribute to a higher performance and downsizing in high-performance hydrogen purifiers.

As is additionally apparent from the above tables, owing to the effects of the niobium included as an alloying element, inventive hydrogen permeable membranes 80 to 107 all have an enhanced hydrogen-separating and permeating ability at an ordinary heating and operating temperature of 300°C and also at an elevated heating and operating temperature of 350°C. That is, production/flow rate of the separated and purified high-purity hydrogen gas increases relative to prior-art hydrogen permeable membranes 25 to 36 which do not contain niobium. In addition, owing to the effects of the phosphorus in membranes 80 to 107 according to the invention, these inventive membranes also have an excellent high-temperature amorphous stability and thus clearly exhibit a much longer service life than prior-art hydrogen permeable membranes 25 to 36, particularly in high-temperature heating operation.

As noted above, in these inventive hydrogen permeable membranes, crystallization is markedly suppressed at elevated temperatures above 300°C. Hence, the membranes exhibit an excellent hydrogen-separating and permeating ability while at the same time having an excellent high-temperature amorphous stability that maintains a non-crystalline microstructure. This enables higher performance and downsizing to be achieved in high-performance hydrogen purifiers, in addition to which it allows high-temperature heating operation to be carried out, contributing to an even further improvement in productivity.